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Research issues related to the appropriate use of FRP in concrete structures

Tim Ibell¹, Antony Darby¹ and Steve Denton²

¹*Department of Architecture and Civil Engineering, University of Bath, Bath, BA2 7AY, UK*

²*Parsons Brinckerhoff, Queen Victoria House, Redland Hill, Redland, Bristol, BS6 6US, UK*

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Corresponding author:

Tim Ibell
Department of Architecture and Civil Engineering
University of Bath
Bath
BA2 7AY
United Kingdom
Tel: 01225 386365
Fax: 01225 386691
Email: T.J.Ibell@bath.ac.uk

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Abstract

This paper describes recently-completed research at the University of Bath within the BRE Centre of Innovative Construction Materials in the field of fibre-reinforced polymer (FRP) materials for use in concrete structures. The research described has been carried out in collaboration with Parsons Brinckerhoff, Bristol. The use of FRP to strengthen concrete structures is a mainstream technology throughout the world, and specific research projects aimed at better understanding the underlying mechanics of this technique are described here. Further, the use of FRP to internally reinforce concrete structures is described in the context of effective use of all materials, coupled with the assurance of ductile behaviour.

Keywords: concrete, fibre-reinforced polymer, FRP

1 INTRODUCTION

1.1 FRP strengthening

The technique of strengthening existing concrete structures using fibre-reinforced polymer (FRP) materials is mainstream and well documented. However, there are several issues which remain unresolved during detailed design of such schemes. Many of these issues have either recently, or are being presently, looked at in some detail within the BRE Centre of Innovative Construction Materials at the University of Bath in the United Kingdom. This paper describes this work.

1.2 FRP reinforcement

An area in which FRP materials are used in niche applications is to reinforce concrete structures. When steel reinforcement corrosion or electromagnetism is considered problematic, polymeric reinforcement may be used instead. However, such use should be based on rationally-based mechanics of the problem, as using FRP as a direct substitution for steel bars is problematic, as will be discussed.

2 CONCRETE SOCIETY TR55 REPORT

In 2003, the University of Bath was commissioned to lead revision of the Concrete Society TR55 Report 'Design guidance for strengthening concrete structures using fibre

composite materials' [8]. The committee comprised consultants, contractors, clients, manufacturers and academics. The decision to revise the 4-year-old document was taken due to major research progress which had been made worldwide since 2000, and due to the global market which both the technique and the document reflected.

Major revisions, additions and clarifications to the document included the overall basis of design (by moving away from a balanced-section approach), transparency of failure mechanisms and checks, material properties, safety factors, behaviour under extreme forms of loading (including impact, blast and vandalism), anchorage, near-surface mounted (NSM) reinforcement, prestressed FRP, concave soffits, strengthening under live load and thick-layered laminates.

For shear strengthening, the revisions were even more fundamental. Explicit checks were introduced to allow for debonding of the FRP, as might be expected. However, due to the fact that almost all test data in this field represents small specimens, size effect was recognized as a key issue, and a check on overall strain (displacement) across shear discontinuities was introduced [9]. Further, the possibility of NSM shear strengthening is now included.

Columns can be strengthened axially by providing confinement by wrapping in the hoop direction. Flexural strengthening may be enhanced by additional longitudinal FRP. For circular columns, the original guidelines treated strengthening in compression and flexure

separately. The new TR55 unifies the design approach using common stress-strain and failure behavior models. Explicit guidelines on strengthening square and rectangular columns have been added, based upon recent research, although only modest increases in axial strength can be achieved.

A new chapter referring to emerging technologies and techniques was written. Whilst these techniques may not currently be at a stage where designers can confidently use them, the chapter presents the important practical aspects of the techniques. The designer can then make an informed judgment as to the suitability of the technique for the particular situation and thus allow further investigation into the details of the method to be made. The emerging technologies that were included are:

- ***Technologies already used in practice***
 - FRP anchorage techniques
 - Concrete masonry walls
 - Strengthening against blast
- ***Technologies at the research stage***
 - Gradually-anchored prestressed CFRP laminates
 - Prestressed NSM bars
 - FRP anchor systems
 - Steel-reinforced polymers
 - Moment redistribution

- Deep embedded bar for shear strengthening
- Prestressed CFRP straps for shear strengthening
- Mechanical fastening techniques
- Strengthening for torsion
- Life expectancy modelling

3 EXPERT SYSTEM FOR FRP DESIGN

As part of a major ongoing Missouri Department of Transportation research contract with the University of Missouri-Rolla in the United States [21], of which the first author is a co-investigator, an Expert System for the design of FRP strengthening schemes has been written [11].

The Expert System allows an inexperienced designer to be led through a decision tree involving a series of Yes-No questions, with explanations at every stage. Not only does this system lead to superior design, but it also allows self-learning in the basic principles of FRP strengthening of concrete bridges. This addresses the crucial need for education in using these generally-unfamiliar materials in the construction industry, as this is not yet a mainstream university-taught issue. Figure 1 shows the opening page of this software. A more general expert system for FRP strengthening is currently under development.

4 CURVED SOFFITS

Many concrete bridges contain concavely-curved soffits, whether this be intentional or not. If intentional, the concavity is usually global across the entire span. If unintentional, it is usually more local. Either way, this concave unevenness is problematic. When the tension-face FRP attempts to stretch, it straightens, leading to premature debonding from the concrete [10,23,24].

Guidelines across the world recognise this effect to a greater or lesser extent, and usually unevenness of about 5mm for every straight length of 1000mm on the soffit is considered to be acceptable prior to strengthening. Research has shown that this degree of unevenness is still problematic if it exists globally across the span, but it is a practical limit for schemes where only local concavity appears [10,23,24]. Figure 2 shows beams which were tested for this concave effect. Also shown is the ‘fan-anchor’ system which was used to overcome the premature debonding behaviour. It was shown to work exceptionally well, returning the beam to more than its flat-soffit fully-strengthened capacity [10].

In essence, global concavity led to a loss in strengthening effect of 30%. This compares with a less severe 15% loss when the concavity was local [10].

5 STRENGTHENING UNDER LIVE LOAD

One of the great benefits of using FRP to strengthen an existing concrete bridge is the speed of application. However, this speed is potentially compromised if the traffic is halted on the bridge during the works. Therefore, it is clearly beneficial for the bridge to be able to withstand dynamic live loading during cure of the adhesive.

Research at Bath and elsewhere [18] has shown that the adhesive is undoubtedly adversely affected by the transient loading during cure. However, given that the concrete itself is the weak link in the bonding process, the reduction in adhesive effectiveness does not seem to be in any way detrimental to the overall FRP bond (this is not true for metallic bridges, where the adhesive itself is the weak link). The Bath research did, however, indicate that a residual compressive strain remained in the FRP. This stress level was equal in magnitude to about half the maximum tensile strain which would have resulted in the FRP under full live load had the strengthening process been carried out without cyclic live loading. Whether this occurs in practice under variable moving live loads is debatable, but needs further investigation.

6 RECTANGULAR WRAPPED COLUMNS

When circular concrete columns are wrapped using FRP material, there are many potential beneficial effects on strengthening. Flexural tensile strength, shear resistance

and axial capacity may all be increased. Further, and probably most significant of all, the strain capacity of the concrete is increased due to excellent confining behaviour, leading to improved ductility and increased flexural strength. While square and rectangular columns also benefit from FRP wrapping, the confinement effect is less pronounced than in the circular case, due to the lack of convex curvature along the straight edges of the section. This means that the corners of the section are well confined, but not the entire cross section [7].

Recent tests have shown that the degree of confinement which rectangular columns experience when wrapped is indeed well defined in the new TR55 document, which itself is based on the model suggested by Teng *et al.* [27]. This model suggests the use of a cruciform zone of confinement, although the precise details of this have been modified for the TR55 document.

TR55 imposes a limit on maximum dimension and aspect ratio (1: 1.5) for rectangular columns, which represents experimental limitations as much as anything. Testing which has just been completed has looked at aspect ratios in this range, and also higher values, in order that future alterations to TR55 may incorporate relaxations on dimensions and aspect ratios. The results suggest that the effect of the FRP on higher aspect-ratio rectangular columns falls off markedly, which is as expected. For the time being, it is therefore suggested that FRP wrapping of rectangular columns should be carried out with due diligence.

Present funded research is aimed at the issues of realistically-sized and loaded non-circular columns. This is because shear stress will exist between concrete and FRP in non-circular columns. Such shear stress could lead to debonding, which in turn would lead to a reduction in FRP strain and a consequent reduction in confinement. This effect will be exacerbated for large-scale and/or eccentrically-loaded columns.

7 REDISTRIBUTION OF BENDING MOMENT

In continuous concrete structures, it is usually the case that the real bending moment distribution is not known with any certainty. This could be due to support settlements, varying earth pressures or movements of the structure during or after construction. This is potentially a serious situation when FRP strengthening is considered, as it might be that, unwittingly, moment redistribution out of a strengthened zone is required in reality.

It seems sensible that redistribution *into* a strengthened zone should be allowed, as no additional demand on ductility is required under such circumstances. However, redistribution *out of* a strengthened zone is far more problematic, as there is a definite demand on rotation capacity under such circumstances [25]. Figure 3 shows an analytical prediction for the moment-curvature relationship in an FRP-strengthened concrete beam, under increasing quantities of FRP (added to help resist live load only, and added at an assumed existing dead-load moment of 35% of the unstrengthened capacity). Ultimate

capacity of the beam is controlled by FRP delamination or concrete crushing in each case, and the Figure shows how the curvature tends to reduce under ever increasing quantities of FRP. This, in turn, reduces the rotation capacity of the section, signifying that moment redistribution is limited out of such zones. But how limited is it?

A theoretical treatise of this is presented elsewhere [25], and it is shown there that if the curvature ductility of the section (ultimate curvature divided by curvature at first yield) is greater than about 2.5, then redistribution should be allowed up to 20%, in accordance with ductility demands laid down for redistribution in ACI-318 [1].

Figure 4 shows a typical plot of curvature ductility against the degree of FRP strengthening. It may be seen that in the practical strengthening limits (anything up to about 0.5%), the curvature ductility requirement to be higher than 2.5 is usually met. This implies that limited moment redistribution should be possible *out of* strengthened zones. However, recent tests [13] have cast doubt on this. In these tests, it was found that moment redistribution out of strengthened zones did not occur at all, whereas moment redistribution into strengthened zones was fully mobilised.

8 SIZE EFFECT: SHEAR STRENGTHENING

The use of FRP sheet to strengthen concrete beams, columns and walls in shear is a well-documented technique, and the effectiveness of this system has been tested on many

laboratory specimens over several years. However, up until recently, there had been no test conducted anywhere in the world on specimens greater than 600mm deep [9].

This is a major issue. If the FRP sheet is fully wrapped (typical for a column) or U-wrapped and mechanically anchored (just below the flange of a T-beam, for instance), then any shear cracking will lead to local debonding of the FRP. Such debonding will extend the full depth of the FRP, and it will strain between anchored locations as the shear discontinuity widens. If the beam is shallow, as in most laboratory tests, this strain will be substantial for a modest width of shear crack. However, if the beam is deeper (as is usually the case in reality), then the strain in the FRP will be low for a modest crack width. As the crack width increases, so the concrete contribution will reduce due to a reduction in aggregate interlock, so that the shear resistance will drop, even though the strain in the FRP is rising.

This problem has been overcome in the new version of TR55, by ensuring that various debonding and overall strain checks are made. Verification of this shear strengthening approach is being carried out at the University of Bath at present, where tests have recently been conducted on beams of overall depth 750mm [29].

9 DEEP EMBEDMENT FOR SHEAR

Most research into shear strengthening of concrete structures using FRP sheet has looked at the wrapped solution. This immediately implies that the web of each beam to be strengthened is indeed accessible. However, this is seldom the case in concrete bridges, as the precast concrete beams usually contain a bottom flange which blocks any access to the webs.

Under such circumstances, when shear strengthening has been considered necessary, it has been usual to use vertically-located plated stainless steel bars to provide the necessary additional shear resistance. This technique has the disadvantage that access to both top and bottom of the web is required (traffic disruption is severe).

Research which is ongoing has already shown that using FRP bars, glued into drilled holes in the web, adds substantial shear strength to such structures [28]. Further, the holes need only be drilled upwards from the soffit, with no disruption to the top surface. Figure 5 shows a typical beam which was strengthened in shear using deep-embedment FRP bars. A theoretical model has been produced, and shown to accurately reflect the additional shear resistance. Moreover, this technique carries with it no danger of surface spalling when NSM-strengthening in shear is conducted.

10 SKEW BENDING

When FRP is used to strengthen a concrete structure, it is usual to assume that the FRP acts in its principal direction (aligned with the longitudinal fibres). This certainly is the case for a strengthened beam. However, what of situations where it is not obvious that FRP sheet, for instance, is being stretched in its principal direction? One such situation includes diagonal yield-line patterns criss-crossing FRP sheet at non-orthogonal angles when a slab has been strengthened. Another example would be the strengthening of cantilever slabs on box-section bridges which are then loaded so that the principal bending at the slab cantilever root is not aligned with the fibres.

Research has been conducted into this problem. Figure 6 shows images of various tests which have been conducted on concrete slabs strengthened with FRP sheets which are placed at various angles to the principal axis of bending [5], while Figure 7 shows the oblique nature of failure in the tests compared with the fibre direction [19].

For conventional non-principal-axis bending of steel-reinforced concrete slabs, the well-known geometric factor on flexural capacity is $\cos^2\alpha$ (where α is the angle between the principal axis of bending and the rotation axis of the yield line). It turned out from tests that when FRP sheet was included in flexural resistance, the factor was best represented by $\cos^3\alpha$ [19].

The theoretical explanation for this may lie in the manner in which debonding of the FRP occurs across the yield line. Figure 8 shows the model which has been assumed here for

the deformation (and hence delamination) which the fibres undergo laterally due to non-principal skew bending. The sketch shows the orientation of an FRP fibre (solid line) which it would assume were it to locally debond across an oblique crack in the substrate concrete. The same fibre is shown as a dashed line were it fully-bonded to the concrete either side of the same crack. The dashed-line scenario is impossible to achieve, so that oblique cracking leads to local transverse debonding (solid line). The particular sketch here is for an oblique angle of 24° , although all angles considered in the tests were investigated theoretically, and all inferred similar trends.

Thus, it seems that the FRP debonds laterally across a crack, rather than kinking across it, as might be expected in a steel-reinforced concrete slab. This phenomenon leads to straightening of the FRP over a characteristic length, which is why the obliqueness of the angle (α) becomes important and, indeed, leads to a reduction in capacity of the system according to $\cos^3\alpha$, rather than merely $\cos^2\alpha$. Additionally, debonding occurred at a lower than expected strain. This may be due to mobilization of mode III fracture in addition to the usual mode II fracture at the FRP concrete interface across a crack.

11 FRP-REINFORCED CONCRETE

If FRP reinforcement is to be used successfully and widely in concrete structures, it must be used to its full potential. This means that it must be strained to near to its breaking

capacity under ultimate limit state conditions. When FRP bars are simply placed in concrete as a direct substitute for steel bars, this is impossible to achieve, as the concrete strain capacity is low (around 0.35%), while the FRP strain capacity is high (at least 1.5%). If the neutral axis is anywhere near mid-depth of the section, the FRP will only be strained to a small fraction of what it can safely endure, leading to expensive and inefficient design.

One way round this is to prestress the FRP, so that much of its strain capacity is absorbed by the prestressing. Much work has been carried out at the University of Bath looking at this approach [31], with some success.

However, an altogether cheaper option to achieve the same thing at the ultimate limit state would be to ensure that the concrete could strain to a much higher capacity prior to crushing failure. Were this possible, then the strain in the FRP would significantly increase prior to failure under ever-increasing curvature. Fundamentally, what is required is to confine the concrete triaxially, so that it cannot ‘squeeze’ out of the compression zone during flexural bending. Work has been aimed at trying to find the best way to achieve this confinement, and hence additional strain capacity, in the concrete [32].

11.1 FRP helices

It is a well-known phenomenon that helical reinforcement confines concrete locally. This concept is used widely in anchorage zones of prestressed concrete structures. Work has extended this idea to prove that an FRP helix placed in the compression zone of a concrete beam will exhibit higher flexural and shear capacity, as well as dissipating energy in a controlled, ductile manner at failure [14, 17, 32]. This is crucial to our understanding of what the priorities are in the design of FRP-reinforced concrete structures.

Figure 9 shows a beam which was cast containing helical FRP reinforcement, while Figure 10 shows the same beam after failure. Note that the helix snapped, implying considerable confinement of the concrete prior to failure. In fact, these tests showed that flexural capacity could be enhanced by up to 50% through the appropriate addition of helical reinforcement. Even more importantly, this research showed that shear strength could be enhanced by a similar amount, so that brittle failure could be averted entirely [31].

11.2 Compression reinforcing bars

Another situation where more use could be made of the compression zone in FRP-reinforced concrete beams is the use of compression FRP reinforcement. Presently, such reinforcement is ignored during design for two reasons. Firstly, the strain which such bars are subjected to is usually low (less than 0.3%), so that the overall contribution from such

bars is small. Secondly, there is the problem of creep in such a situation, with the possibility that the compression bars do not hold their stress at a high level indefinitely.

The second problem is easily overcome if one considers that the compression reinforcement will be active only for accidental and/or very briefly-applied live overload. The first problem is easily overcome if the concrete is confined, so that it may strain to around 1% under ductile conditions, thereby allowing the internal compression FRP bars to strain to similar levels. Under such conditions, the compression bars become very useful indeed, and recent research has shown that a 30% increase in capacity can be achieved when one uses both FRP compression bars and also an FRP helix in the compression zone [14, 17].

11.3 Self-compacting fibre-reinforced concrete

Another possible way in which the compression zone may be confined, and hence provided with additional strain capacity, is to use short chopped fibers instead of a continuous helix. Such work has been conducted, and such a system has been shown to be effective [4].

The placement of fibre-reinforced concrete is notoriously difficult due to clumping of the fibers and difficulty in the use of a poker vibrator. These problems may be overcome by using self-compacting concrete which contains short fibres. Prior research has shown that

such concrete has improved tensile strength, strain capacity and ductility over normal concrete [2]. It is also particularly strong (over 100MPa) and very easy to pour into moulds due to its self-compacting ability.

It turns out that such concrete holds major benefits when used in tandem with FRP reinforcing bars [4]. This is because the additional strain capacity allows an increase in flexural strength over the equivalent normally-reinforced beams, for the same reasons as stated previously. A self-compacting, high-strength, fibre-reinforced concrete, used in conjunction with FRP reinforcing bars clearly has major advantages over more traditionally-reinforced concrete structures. It is the authors' belief that only through such novel use of various construction materials will full benefit be extracted from such constituent materials.

12 SIZE EFFECT: FRP REINFORCEMENT

Size effect in steel-reinforced concrete structures is a well-documented problem. Small specimens fail at higher unit stress levels than the equivalent larger ones. However, what about FRP-reinforced concrete structures? Due to the lack of ductility in the FRP, it might be expected that FRP-reinforced concrete structures undergo size effect to an even greater extent than steel-reinforced equivalents.

This is exactly what was found [22]. Figure 11 shows one of the beams which was tested in this series, undergoing catastrophic shear failure. Such shear failure was encountered across all tests, and the results indicated that there was a size effect in the results which followed the BS8110 [3] prediction, namely a power law on the overall depth of -0.25, applied only to the concrete contribution term. In fact, the results were remarkably close to predictions provided by the Institution of Structural Engineers' Interim Guidance on the use of FRP reinforcement in concrete structures [16].

12 ANCHORAGE OF FRP REINFORCEMENT

12.1 FRP-prestressed concrete

It is evident from previous discussions that if FRP is to be used to internally reinforce concrete structures, then it should be used to its full capacity, lest its cost precludes its use on a global scale. One way to achieve this is to pretension the FRP bars to 'remove' much of the initial strain capacity, and to improve serviceability, which usually is the governing criterion in design. However, if prestressing is to be used, then the tendons must be properly anchored and, what is more, the anchorage zone (or end block) must be able to withstand the highly concentrated bursting stresses which such prestressing inevitably produces.

This means that the concrete in the end zone must be reinforced against tensile splitting. However, clearly the use of FRP must be considered here, lest the reasons for prestressing the structure using a non-metallic material are compromised by using a corrosive material in the most highly stressed zone.

Research has shown that the combination of a double helix and an associated mat reinforcement system (see Figure 12) is most effective in preventing bursting failure beneath each anchorage plate (primary zones) within FRP-prestressed end blocks [6].

Using such a system, true ductility in the system may be obtained, as wedge failure beneath each anchorage plate is resisted by the confining effects of the helix and by the tensile strength of the mat. A plasticity-based model has been applied to this problem, with accurate results being obtained [6].

Equally important areas which need thought when designing FRP-prestressed concrete anchorage zones are the so-called 'secondary' zones. Within these zones, the primary zones associated with each anchorage interact with each other, and the flow of stress is extremely complicated.

Figure 13 shows a photograph of one of the many specimens tested as part of this research, demonstrating the type of failures which may be expected in multiply-anchored

end blocks. This work also looked at ways in which these zones may be modeled using both elastic and plastic theoretical tools [12].

12.2 *FRP reinforcing bars*

One of the greatest problems in specifying FRP reinforcing bars is the fact that such bars cannot easily be bent in a factory and cannot be bent at all on site. This throws up the question of anchorage of the main longitudinal FRP bars. If they cannot be bent, then they should be anchored in some other way. Two systems have recently been investigated at the University of Bath [26, 33].

The first system entails the use of an FRP helix which surrounds the longitudinal bars at the ends of the beam. Such a system relies on the bars beginning to pull out, forming a concrete wedge, which then is held fast through the circular confining effect of the helix. Such a system was suggested by Nanni *et al.* [20] to prevent anchorage draw-in of FRP pretensioning bars. While successful in that particular application, its use was found to be wanting under the present circumstances. All bars pulled out of the test set-up with little or no increase in anchorage resistance. This is not to say that the concept does not work for the anchorage of initially stress-free bars. Indeed, it has been shown to be effective in other tests conducted [32]. Rather, it shows that the test set-up used (direct pull-out) was inappropriate, and a beam test set-up should have been used instead.

The second system was much more successful, and is potentially a very practical solution for on-site anchorage requirements. The bars were slit lengthways at their ends (over a length of only 100mm), and the two halves of the bar splayed open by a few millimeters, and wedged into this splayed arrangement using a spacer. This system worked extremely well in preventing pull out, due to the wedge-like behaviour of the bar. Further enhancement was achieved by addition of a surrounding FRP helix which prevented concrete splitting and increased ductility of the anchorage. This concept is to be taken further in future tests, in which the durability of the exposed fibres will be ensured through coating the split ends of the bars in resin.

13 FLEXIBLE FABRIC FORMWORK

Figure 14 shows the construction (Figures 14(a), (b) and (c)) and the testing (Figures 14(d) and (e)) of concrete beams formed using flexible fabric formwork [15]. The purpose of this research was to develop optimum structural and architectural forms which are buildable using a practical technique. This work extended the pioneering work in this field by West [30]. The research led to a formfinding tool for the shape which such beams would take during the casting process. It also led to detailing issues being improved in such beams, and to eccentric loading arrangements being studied. The next goal is to be able to use the fabric formwork as permanent participating reinforcement for such beams, both in flexure and in shear, and this work is underway.

14 CONCLUSIONS

This paper has described many recent and on-going research projects being carried out at the University of Bath under the direction of the authors. The thrust of this work is aimed at the rational use of FRP in concrete structures, so that efficient use is made of it, and its use proliferates.

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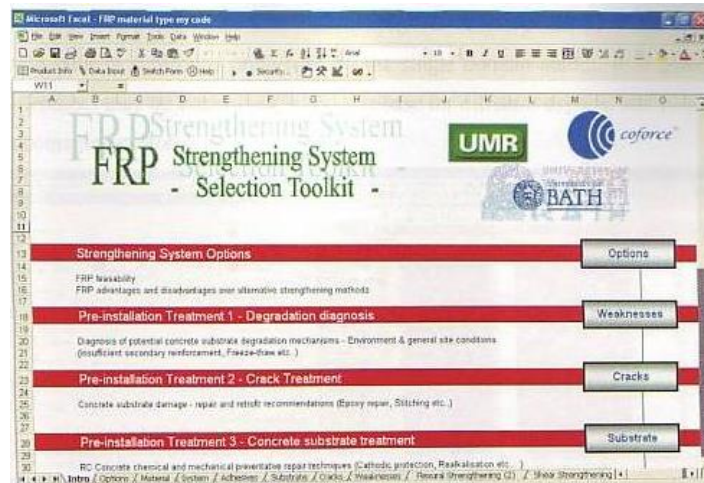


Figure 1. Expert system for FRP strengthening design.



Figure 2. Concave beams for testing.

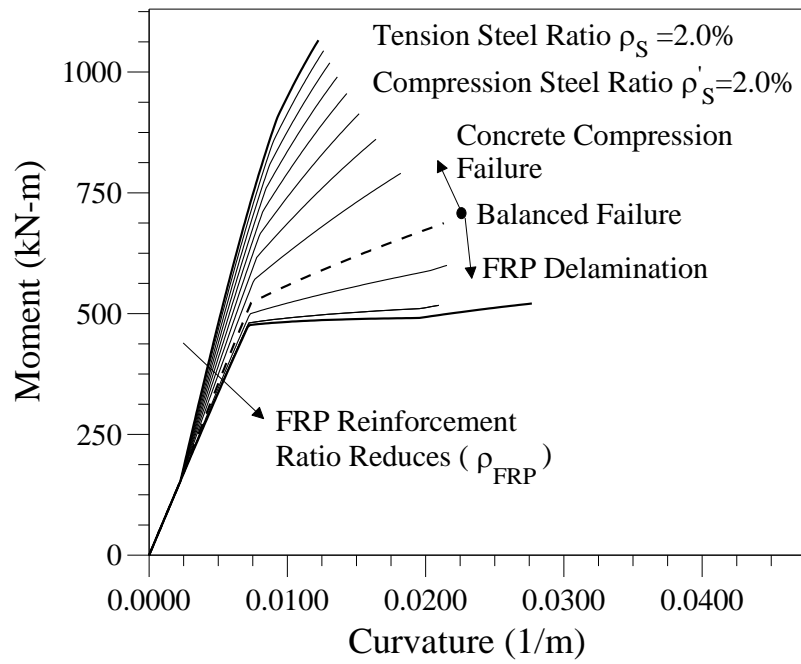


Figure 3. Moment-curvature plots for an FRP-strengthened concrete section.

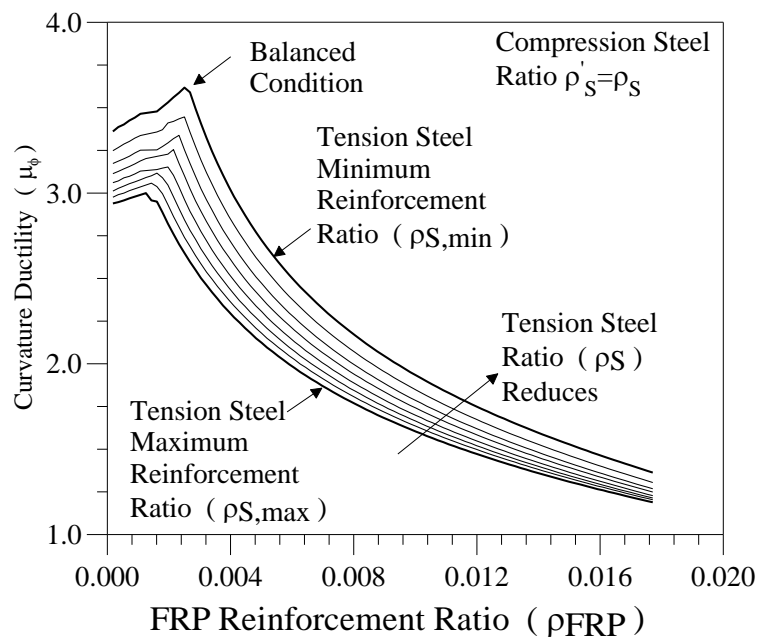


Figure 4. Curvature ductility demands under increasing FRP strengthening ratios.



Figure 5. FRP deep-embedment shear-strengthened concrete beam.



Figure 6. Skew bending tests on FRP-strengthened concrete slabs.



Figure 7. Oblique cracking beneath FRP plate.

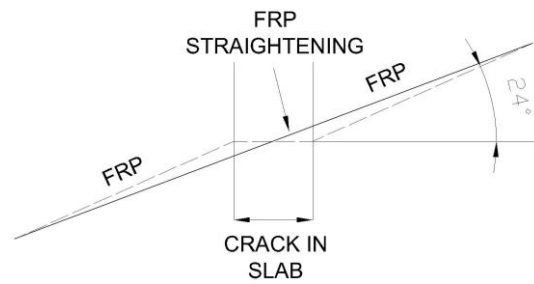


Figure 8. Straightening of FRP across an oblique crack.



Figure 9. FRP helix being tied into reinforcing cage.



Figure 10. FRP helix ruptured at failure.

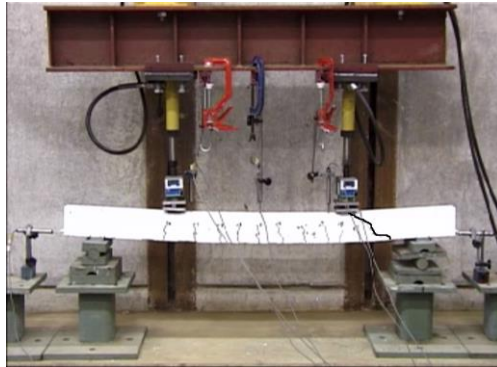


Figure 11. Beam test during size-effect series.

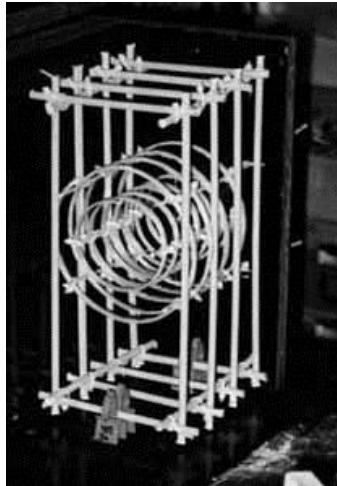


Figure 12. Combined double-helix and mat system.



Figure 13. Interaction between multiple anchorages.



(a)



(d)



(b)



(e)



(c)

Figure 14. Construction and testing of flexible formwork concrete: (a) Initial fabric mould, (b) Casting commenced, (c) Cast specimen still with fabric formwork, (d) Symmetrically-curved specimen under load, and (e) Asymmetrically-curved specimen under asymmetric load.